

Vapour Space Flammability Considerations for Gasoline Compression Ignition Vehicles Operating on “Dieseline” Blends.

Roger Cracknell
Shell

Michael Bardon
Nexum Research Corporation

David Gardiner
Nexum Engine Research & Development Corp

Greg Pucher
Nexum Research Corporation

Heather Hamje and David Rickeard
Concawe

Javier Ariztegui
Repsol

Leonardo Pellegrini
ENI Spa

ABSTRACT

Gasoline Compression Ignition (GCI) has been identified as a technology which could give both high efficiency and relatively low engine-out emissions. The introduction of any new vehicle technology requires widespread availability of appropriate fuels. It would be ideal therefore if GCI vehicles were able to operate using the standard grade of gasoline that is available at the pump. However, in spite of recent progress, operation at idle and low loads still remains a formidable challenge, given the relatively low autoignition reactivity of conventional gasoline at these conditions. One conceivable solution would be to use both diesel and gasoline, either in separate tanks or blended as a single fuel (“dieseline”). However, with this latter option, a major concern for dieseline would be whether a flammable mixture could exist in the vapour space in the fuel tank. It is expected that in a practical scenario, the ambient temperature would generally exceed the Lower Flammability Limit (LFL) temperature of diesel/gasoline blends. A non-flammable vapour could still be assured, however, if the temperature in the fuel tank were above the Upper Flammability Limit (UFL) temperature. To investigate whether a flammable mixture could exist, the Upper Flammability Limit (UFL) temperatures of 12 distinct blends of gasoline, diesel, ethanol and ETBE were investigated in a special combustion chamber designed to mimic a vehicle tank, with a 5% fuel fill level to represent expected worst case conditions. The results should be considered as provisional, but suggest that under realistic assumptions of gasoline DVPE and ambient temperature, nonflammable blends can be achieved with mixtures containing a minimum of 25–40% gasoline. Derived Cetane Numbers up to 36–40 could be achieved, making the fuels suitable for Low Temperature Combustion.

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INTRODUCTION

Compression Ignition (CI) engines, mainly fuelled by diesel, achieve high levels of efficiency and offer the lowest fuel consumption of mainstream internal combustion engine designs. Gasoline spark ignition engines can deliver very low exhaust emissions through the use of stoichiometric three-way catalysts, but cannot match the efficiency of diesel engines. Control of emissions from diesel vehicles, particularly NO_x and particulates, has proved much more challenging. Low Temperature Combustion (LTC) is a compression ignition approach that has the potential to avoid the high engine-out NO_x and particulate emissions associated with conventional diesel vehicles and emissions approaching Euro 6 levels have been demonstrated without the use of exhaust after-treatment. This is achieved by combustng at lower temperatures to reduce NO_x and allowing more time for fuel-air mixing to avoid particulate formation. While such engines can run on conventional diesel fuels, there are advantages in using a fuel of lower cetane number where the longer ignition delay allows more time for mixing. A more volatile fuel also assists in the fuel-air mixing process.

Several researchers have suggested special fuels to facilitate LTC combustion, often similar to refinery naphtha [1,2,3,4,5], however a requirement for a new fuel grade presents a very high barrier to acceptance of a new engine technology since such fuels would need to be widely available even before the number of vehicles requiring them had grown.

Market acceptance would be more likely if fuels currently available at the filling station could be used. For this reason, many researchers have investigated whether pump gasoline could be used as a fuel in a CI engine [5,6,7,8,9,10,11]. Use of gasoline is attractive to address an oversupply of gasoline and an under-supply of diesel and other distillate products. Such a situation exists currently in European refineries where the effort to maximise diesel output is detrimental to refinery efficiency and to CO₂ emissions due to more intensive processing.

However, in spite of recent progress, CI operation on gasoline remains a formidable challenge. Gasoline has a high octane number and conversely a very low cetane number which means that it has low autoignition reactivity. While good ignition of gasoline can be achieved at medium and high loads, it is very difficult to achieve at the lower temperatures and pressures associated with idle and light load conditions.

One conceivable solution would be to use both diesel and gasoline, either in separate tanks or blended as a single fuel ("dieseline") [12,13,14,15,16,17,18]. Although this fuel is not currently available in filling stations it could be supplied by blending at the fuel pump, which would be a less costly option than producing a completely separate fuel grade. This would provide a fuel with a lower cetane number and higher volatility than diesel, while avoiding the extreme ignitability problems of pure gasoline. A vehicle using such a fuel would require evaporative emission controls as for a gasoline engine. It would also need to be verified that the lubricity of the fuel was compatible with the engine's fuel injection equipment, however as the

injection pressure used on gasoline engines increases [19] this is becoming less of an issue. If necessary, adequate lubricity levels can still be achieved by using suitable additives.

Kawano et al studied mixtures of diesel and gasoline to facilitate Homogeneous Charge Compression Ignition (HCCI) in a diesel engine and discussed the effects of different fuel properties [14]. More recently, performance of Dieseline blends have been studied by Zhang, Xu et al [16,17,18] in a bench engine operating in partially pre-mixed conditions with the objective of achieving CI engine efficiency and low emissions. They found that with a blend of 50% gasoline in diesel, the total particle number concentration could be reduced by 90% and NO_x levels remained low. Concawe [19] found that a dieseline blend at 44CN performed well in a bench engine and gave lower PM emissions than diesel fuel at Euro 6 NO_x levels in both engine and vehicle tests.

A more fundamental concern relates to the range of fuels that can be used safely in the vehicle without increasing the risk of fire. The fuel tank of a vehicle contains a large amount of flammable material, but since combustion occurs in the vapour phase, it is the air and vapour mix in the space above the liquid fuel that is important for safety. Diesel fuel has a relatively high boiling range and under normal operating temperatures the amount of fuel vapour in the tank is too low to support combustion. The diesel fuel flash point Flash Point [22] specification measures the lowest temperature at which the vapour-air mixture will ignite when an ignition source is presented. The specification set in Europe by standard EN 590 is greater than 55 °C.

Gasoline is much more volatile than diesel and introduction of even less than 1% of gasoline into a diesel fuel can result in a flammable mixture above the liquid fuel at normal ambient temperatures. Gasoline vehicles avoid a flammable mixture in the fuel tank because gasoline is so volatile at most ambient temperatures that the headspace vapours in the tank are too rich to burn. Gasoline dry vapour pressure equivalent (DVPE) is referenced at a standard test temperature with maximum limits set for emissions reasons. The allowed DVPE varies with the seasonal and geographical climatic conditions.

The DVPE of a fuel is measured at a standard test temperature and is a function of its composition. The actual vapour pressure of a fuel in the fuel temperature varies with the fuel tank temperature. The flammability of the vapour-air mixture will also be influenced by the fuel fill level which affects the liquid/vapour ratio. However in addition to the flammability of the mixture per se, there is also the consideration as to whether a flame kernel could actually propagate in the tank. This will be affected by the specific geometry of the fuel tank. Therefore, for a given configuration and fuel, the flammability of the vapour-air mixture varies with temperature. At very low temperatures, vapour pressure is low and the mixture is too lean to support combustion. As the temperature rises a temperature is reached where ignition and sustained combustion is possible and this is termed the Lower Flammability Limit (LFL) temperature. As temperature is further increased, the mixture remains flammable until at the high temperature boundary of the region the Upper

Flammability Limit (UFL) is reached, beyond which (with increasing temperatures) so much fuel is evaporated that the mixture becomes too rich to support combustion.

Thus, the relatively high volatility of typical gasoline blends results in air and fuel vapour mixtures which are generally too rich to ignite within tanks at most ambient temperatures, meaning that conditions are above the UFL. Applying the same principle, for safe operation of diesel-gasoline mixtures, we should choose blends for which the vapour-air mix in the fuel tank remains above the UFL temperature over the normal range of operating temperatures of the vehicle.

CRC [21] studied the UFL temperatures of gasolines with and without ethanol. They found that the presence of ethanol increased the UFL by 3-5°C depending on the vapour pressure of the gasoline. Work by Saudi-Aramco [23] measured Flash Points in blends of diesel and gasoline. They found that the Flash Point fell to -40°C when the blend contained 16% gasoline, close to the figure of -45°C for pure gasoline. In a more recent article, most of the same authors have studied and modeled the flammability and volatility properties of “dieseline”-like binary mixtures [24]. They concluded that diesel blending has little impact on the vapor pressure characteristics of gasoline up to 50% by volume while for diesel contents higher than 50% v/v the vapour pressure requirements for safe operation can be adjusted by the addition of butane.

Gardiner et al developed a Flammability Test Chamber laboratory test that simulates conditions in a vehicle fuel tank and allows a direct measurement of UFL temperature. The method has been applied to gasoline-ethanol mixtures [25,26,27] and in this study has been adopted to study diesel-gasoline mixtures.

EXPERIMENTAL STUDIES

To explore the flammability of air/fuel vapour mixtures in tanks containing dieseline fuel, an experimental study was undertaken to determine the UFL temperatures of 12 distinct fuel blends which covered a wide range of the relative proportion of typical diesel and gasoline fuels. The base fuels which were used in these blends consisted of one type of diesel, 4 types of gasoline, and also neat ethanol (added to 4 of the 12 blends). The 4 gasoline base fuels had distinct vapour pressure values, and one of them contained ETBE, an oxygenate component. Using experimental techniques that were employed in previous studies to examine the flammability of fuel tank headspace vapours above 2 gasoline and ethanol blends [25,26,27], UFL temperatures were determined for the 12 fuel blends. Sealed chambers fitted with internal ignition sources and pressure transducers (to detect combustion) were placed in a temperature controlled environmental chamber. For safe operation, we are looking to achieve a fuel-rich mixture in the vapour space, so the most critical conditions occur when the fuel level is low. A 5% fuel fill level was chosen to represent the likely worst case scenario, and the UFL temperatures were determined for the blends with this fill level.

Sample Preparation

The components used for the test fuel blends are shown in Table 1. Although these gasolines were nominally ethanol free (E0), our GC data showed that all four base gasolines had some ethanol, ranging from 0.2 mass% for G1 to over 3% for G3.

Table 1. Components used in the test fuel blends

Base Fuel	Description
Diesel	European ULSD, 5% FAME, Cloud Point: -4°C, CN=51
Gasoline G1	45 kPa DVPE gasoline, summer blend (E0), RON=96.3
Gasoline G2	60 kPa DVPE gasoline, mid-season blend (E0), RON=95.1
Gasoline G3	90 kPa DVPE gasoline, winter blend (E0), RON=94.4
Gasoline G4	54 kPa DVPE gasoline, containing ETBE (E0), RON=98.6
Ethanol	Neat ethanol containing no denaturant

12 fuel blends were prepared for UFL combustion testing as shown in Table 2.

Table 2. Fuel Blend Volumetric Proportions

Blend	Diesel (%)	G1 (%)	G2 (%)	G3 (%)	G4 (%)	Ethanol (%)
1	90	10				
2	81	9				10
3	75	25				
4	71.25	23.75				5
5	67.5	22.5				10
6	60	40				
7	54	36				10
8	75		25			
9	90			10		
10	75			25		
11	60			40		
12	75				25	

The gasoline concentrations in the blends ranged from up to 40% by volume with the balance made up of diesel fuel, except where ethanol was present. Ethanol was added at the relatively high concentrations of 5% or 10% volume in the total blend, meaning that the proportion relative to the gasoline component was much higher. A wide range of blends was made using the summer grade gasoline G1, with crosschecks at least at 25% on the other gasolines.

To minimize the loss of higher volatility components, fuel stocks were pre-chilled to approximately 0°C prior to blending, and quantities withdrawn by siphoning. Density was first determined for each of the base fuels, and the blending was executed on a mass-basis according to target proportions. Each sample container was filled to 850 mL, and blend constituents were typically added to within the 1g resolution of the scale used. Blend accuracy was checked by calculating a target blend density and comparing this with the